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Endoscopic optical coherence tomographic imaging with a CMOS-MEMS micromirror☆

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Abstract

This paper reports a single-crystalline silicon (SCS) micromirror used for laser beam scanning in an endoscopic optical coherence tomography (OCT) system. The micromirror is fabricated by using a deep reactive-ion-etch (DRIE) post-CMOS micromachining process. Thin bimorph actuation structures and movable bulk silicon structures are simultaneously achieved. The micromirror is 1 mm by 1 mm in size, coated with aluminum, and thermally actuated by an integrated polysilicon heater. The radius of curvature of the mirror surface is 50 cm. The mirror has a resonance frequency of 165 Hz and rotates 17° when a 15 mA d.c. current is applied. A discontinuity in the dynamic response curve is observed. By using a white-light profilometer, we found that the discontinuity is caused by localized buckling of the bimorph actuation mesh. Cross-sectional images of 500×1000 pixels covering an area of 2.9 mm by 2.8 mm are acquired at 5 frames/s by using an OCT system based on this micromirror.

Keywords: Micromirror; Single-crystal silicon; Bimorph; Optical coherence tomography (OCT)

1. Introduction

Numerous micromirrors have been demonstrated by using either surface- or bulk-micromachining processes [1,2]. Nevertheless, micromachined large, flat mirrors with large tunable displacement or rotation angle required by some applications such as medical imaging, interferometer systems and laser beam steering are rarely reported but are demanding more attention. For example, current endoscopic optical coherence tomography (OCT) devices for in vivo imaging of internal organs use either a rotating hollow cable carrying a single-mode optical fiber or a small galvanometric plate swinging the distal fiber tip to perform transverse scanning [3,4]. If the scanning devices can be replaced by a micromirror, endoscopic OCT systems may be more compact and potentially low cost. However, the micromirror must be flat and large to maintain high light-coupling efficiency and spatial resolution, and must have large rotation angle to meet the scanning range.

Conant et al. [5] reported a single-crystalline silicon (SCS)-based micromirror with a diameter of 550 μm for high speed scanning (34 kHz) by using silicon-on-insulator (SOI) wafers and two-side alignment. Su et al. [6] demonstrated a flat, 0.25 mm by 0.25 mm mirror by assembling an SCS mirror on top of polysilicon actuators. However, using high voltage to achieve a large rotation angle is still a problem for interior body applications.

In prior research, multilayer metal/silicon oxide beams have included an embedded polysilicon heater to tune the resonant frequency of a gyroscope's drive mode [7]. Similar to the thermally actuated micromirror reported in [8], the beams bend down when a current is applied to the polysilicon heater. Using the same concept and combining a deep reactive-ion-etch (DRIE) CMOS-MEMS process [9], we have developed a bulk-Si mirror actuated electro-thermally to a large rotation angle. The operational principle and mirror design are introduced first, followed by the detailed

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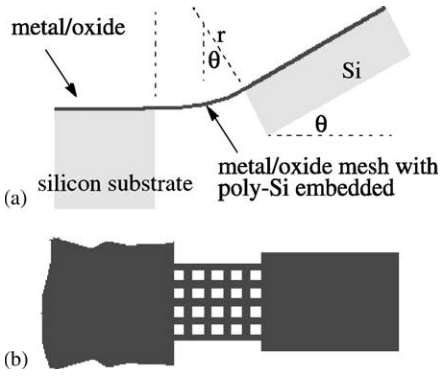


Fig. 1. The mirror conceptual design: (a) cross-sectional view and (b) top view.

fabrication procedure, the characterization results of the mirror flatness and laser-scanning static response, and application of the micromirror to an OCT system.

2. Mirror design

The schematic of the mirror design is shown in Fig. 1. The mirror is attached to a bi-layer aluminum/silicon dioxide mesh with polysilicon encapsulated within the silicon dioxide to form a bimorph thermal actuator. The mesh curls up after being released due to the tensile stress in the aluminum layer and compressive residual stress in the bottom silicon dioxide layer. Therefore, the radius of curvature of a bimorph beam is determined by both the initial curling and the temperature change from the polysilicon heating, and is given by $1/r = 1/R_0 - 1/r_T$, where r is the actual radius of curvature, R_0 is the initial radius of curvature and r_T is the radius of curvature due to the temperature change. By ignoring the thin polysilicon layer, r_T is readily derived as [10]

$$\frac{1}{r_T}=\frac{2}{3}\frac{t_1^2+t_2^2+(3/2)t_1t_2+(1/4)((E_1t_1^3/E_2t_2)+(E_2t_2^3/E_1t_1))}{\Delta T(\alpha_1-\alpha_2)(t_1-t_2)},$$

where t_i, E_i and α_i are the thickness, Young's modulus and thermal expansion coefficient of the metal layer ($i = 1$) and the oxide layer ($i = 2$), respectively, and ΔT the temperature change on the beam. R_0 is a fixed value for a given process. For instance, the radius of curvature of micromechanical beams made of metal-1/oxide layers in the Agilent 0.5 μm 3-metal CMOS process was measured to be 290 μm [11].

A bulk silicon mirror coated with metal and dielectrics is attached at the end of the mesh. The tilt of the mirror follows the curvature of the mesh, and is given by $\theta = L/r$, where L is the length of the mesh. The choice of L depends on the requirements to speed and power consumption, and rigidity of the mirror assembly.

3. Fabrication

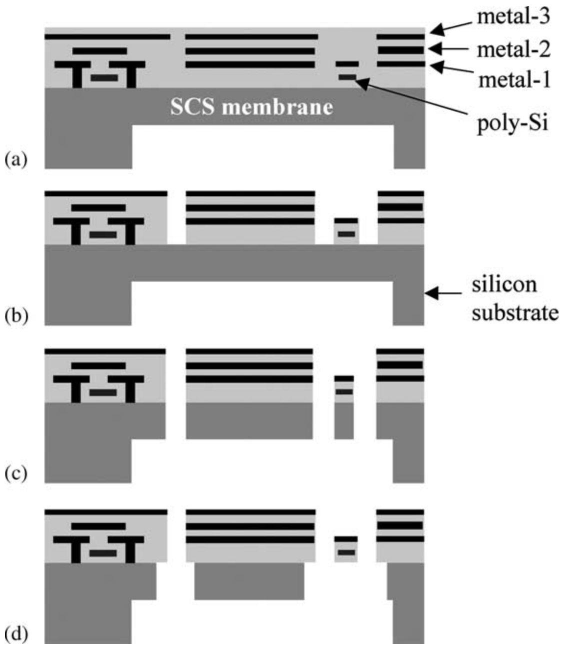


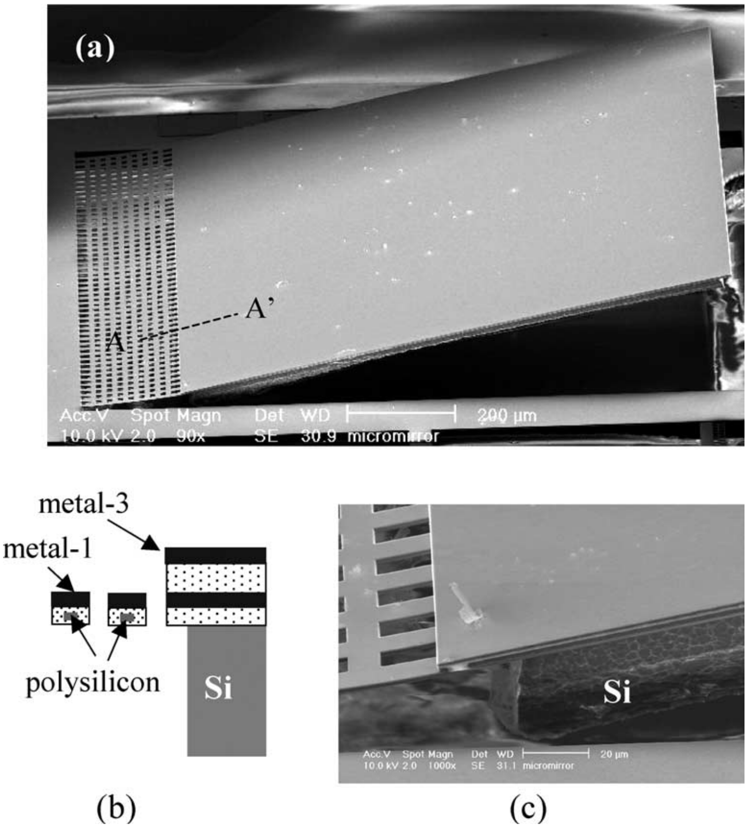
Fig. 2. DRIE CMOS-MEMS process flow: (a) backside etch, (b) oxide etch, (c) deep Si etch and (d) Si undercut.

The micromirror is fabricated with a DRIE CMOS-MEMS process [9]. The process flow starts with a deep anisotropic backside etch leaving a 10 to 100 μm thick SCS membrane with thickness dependent on etch time (Fig. 2(a)). This thick SCS membrane is used as the mechanical support of the mirror to keep the mirror flat. The cavity formed by the backside etch leaves ample space for large actuation range. Next, an anisotropic dielectric etch is performed from the front side (Fig. 2(b)), followed by a directional silicon etch (Fig. 2(c)). Finally, an isotropic Si etch is performed to undercut the silicon underneath the mesh (Fig. 2(d)). The mesh is 1.8 μm thick and thus flexible in the z-direction (out-of-plane).

This process is maskless, only uses dry etch steps, is completely compatible with commercial CMOS processes and has no release sticking problems. Fig. 3(a) shows a scanning electron micrograph (SEM) of a fabricated micromirror. The mirror tilts 17° at room temperature because of the residual stress. The bimorph actuation mesh consists of metal-1 and oxide with an embedded polysilicon resistor. The cross-section view is shown in Fig. 3(b). Fig. 3(c) is a close-up of one corner of the mirror showing the supporting 40 μm thick bulk silicon underneath the mirror Al surface.

4. Characterization

The structural SCS layer backing the mirror provides very good flatness across the 1 mm surface. Fig. 4 shows the surface profile of the active mirror area measured by using a Wyko NT2000 optical profilometer. The peak-to-valley deflection is 0.5 μm, which converts to a radius of curvature of 50 cm. The mirror can be even flatter if the SCS



(b) (c)

Fig. 3. SEMs of a released mirror: (a) side view, (b) cross-section of A–A′ and (c) close-up of one corner.

membrane is made thicker during the backside etch step (Fig. 2(a)).

Fig. 5 shows the measured rotation angle at different heater currents. When the applied current increases, the mirror rotates downward. The resistance of the heater is 2.4 kΩ. The maximum current the polysilicon heater can carry before thermal damage occurs is 18 mA. The two curves in Fig. 5 correspond to the increasing and decreasing currents, respectively. Note that the backward curve shifts a little bit to the left of the forward curve. This hysteresis is due to the thermal relaxation time. Also note that both of the curves have a discontinuity, i.e., the mirror jumps at a certain applied current.

In order to understand why this jump occurs, the white-light profilometer was employed to measure the surface profile of the bimorph actuation mesh before and after the jump. The measured results are shown in Fig. 6. The mesh curls uniformly before the jump (Fig. 6(a)), but the mesh becomes buckled instantly when the jump happens (Fig. 6(b)). A wider view of the mesh right after the jump is shown in Fig. 6(c).

A comprehensive reliability test of the micromirror has not been undertaken. However, one micromirror has been continuously working at a 2 Hz scan rate for more than 16

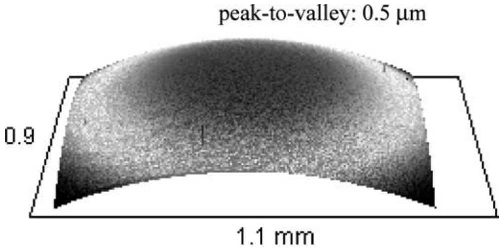


Fig. 4. Surface profile of the micromirror.

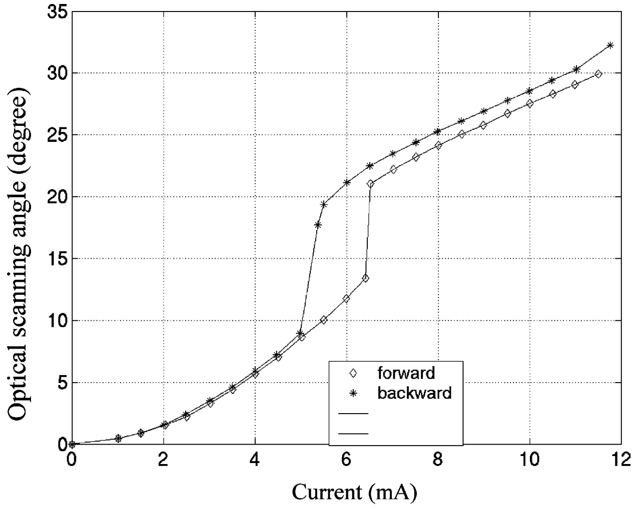


Fig. 5. Optical scanning angle versus applied current.

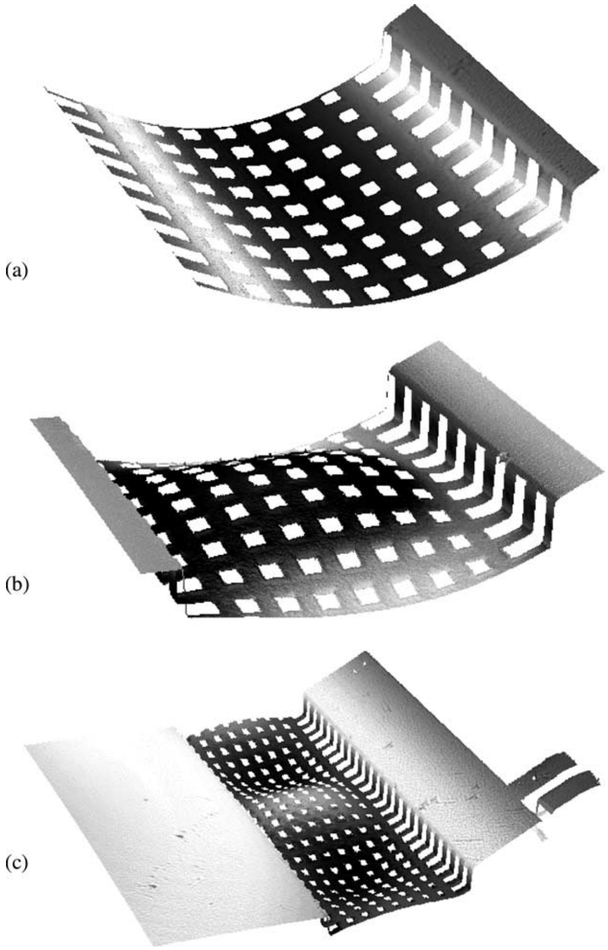


Fig. 6. Profile of the bimorph actuation mesh before and after the jump: (a) before jump, (b) after jump and (c) wider view after jump.

months, corresponding to 83 million cycles. No significant degradation or aging is observed. The resonant frequency of the mirror is 165 Hz, which exceeds the scanning speed requirement of 100 Hz for most endoscopic applications.

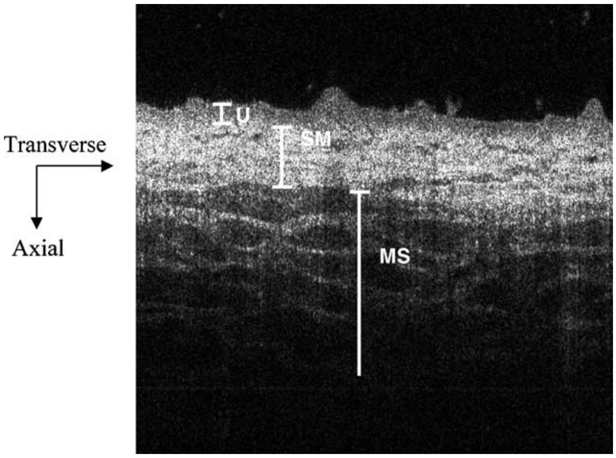


Fig. 8. In vivo 2-D endoscopic OCT image of porcine bladder through cystotomy. U: urothelium, SM: submucosa, MS: muscularis layer. Image size: 500 × 1000 pixels covering an area of 2.9 mm × 2.8 mm.

5. An OCT imaging application

Fig. 7 illustrates a 5 mm diameter endoscopic OCT system equipped with the above micromirror [12]. A broadband light source is guided equally into two single-mode fibers through a beam splitter to form a Michelson interferometer. The light in the sample arm is collimated by a fiber-optic aspherical lens, deflected by a conventional mirror and the beam steering micromirror. It is then focused on the detecting biological sample, which reflects part of the incident light back to the sample arm. The light in the reference arm is linearly scanned in the axial direction by an optical delay line. Because broadband light has short temporal coherence, this will permit detection of backscattering from different depth within the biological sample. Fig. 8 is an OCT image of a porcine urinary bladder in vivo (through cystotomy), demonstrating that the endoscopic OCT system using an MEMS micromirror can delineate the morphology of the bladder at high resolution. The optical power delivered to the testing sample is 2.0–2.5 mW. The

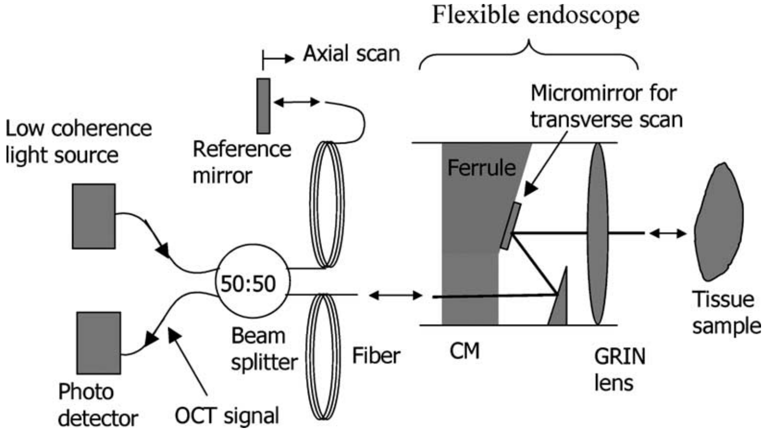


Fig. 7. Schematic of the MEMS-based endoscopic OCT system. CM: collimator. The OCT signal is the combination of the reference source and the reflected light from the sample, which creates the interference pattern. The external reference mirror moves for axial scan of the sample.

diameter of the laser beam focused on the sample is about 20 μm. Since the transverse scanning is operated by the micromirror inside the endoscope, no mechanical movement of the endoscope is needed. Integration of the micromirror offers the opportunity to develop compact, low-cost laser-scanning endoscopes for noninvasive or minimally invasive imaging diagnosis within a wide variety of inner organs.

6. Conclusions and future work

A large, flat bulk-Si CMOS-MEMS mirror was demonstrated and applied to an OCT endoscope for in vivo medical imaging. The fabrication process is simple and compatible with conventional CMOS processes. Rotation sensors and angular control circuits can be integrated on the same chip with the mirrors. This type of micromirror is especially suitable for laser-scanning endoscopy that requires large rotation angle and low drive voltage.

The bimorph actuation mesh design needs to be improved to minimize or even eliminate the buckling either by releasing the transverse stress or uniformly distributing the generated heat. Polysilicon temperature and stress sensors can also be integrated to track the rotation angle.

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Biographies

Huikai Xie is an Assistant Professor at the Department of Electrical and Computer Engineering of the University of Florida. He received his MS in electrical engineering and computer science from Tufts University in 1998, and PhD degree in electrical and computer engineering from Carnegie Mellon University in 2002. He also holds BS and MS degrees in electronic engineering from Beijing Institute of Technology. From 1992 to 1996, he was a research faculty member in the Institute of Microelectronics at Tsinghua University, Beijing, working on various silicon-based chemical and mechanical sensors. He spent Summer 2001 at the North America Research Center of Robert Bosch Corporation designing a 6-DOF inertial measurement unit. His present research interests include integrated inertial sensors, optical MEMS, biomedical sensing and imaging, microfabrication technologies and MEMS multidomain simulation.

Yingtian Pan is an Assistant Professor at University of Pittsburgh holding a joint appointment with the Department of Medicine and Department of Bioengineering. Since 1993, he has been working on noninvasive optical imaging and spectroscopy of biological tissue. His current research interest is on development of laser-scanning endoscopy for early cancer detection. He has over 30 journal publications.

Gary K. Fedder is an Associate Professor at Carnegie Mellon University holding a joint appointment with the Department of Electrical and Computer Engineering and The Robotics Institute. He received the BS and MS degrees in electrical engineering from MIT in 1982 and 1984, respectively. From 1984 to 1989, he worked at the Hewlett-Packard Company on circuit design and printed-circuit modeling. In 1994, he received the PhD degree from U. C. Berkeley, where his research resulted in the first demonstration of multimode control of a underdamped surface-micromachined inertial device. He received the 1993 AIME Electronic Materials Society Ross Tucker Award, the 1996 Carnegie Institute of Technology G.T. Ladd Award, and the 1996 NSF CAREER Award. His present research interests include microsensor and microactuator design and modeling, integrated MEMS manufactured in CMOS processes and structured design methodologies for MEMS.